HOW DID IT ALL BEGIN?

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How did it all begin? Although this question has undoubtedly lingered for as long as humans have walked the Earth, the answer still eludes us. Yet since my grandparents were born, scientists have been able to refine this question to a degree I find truly remarkable. In this brief essay, I describe some of my own past and ongoing work on this topic, centering on cosmological inflation. I focus on (1) observationally testing whether this picture is correct and (2) working out implications for the nature of physical reality (*e.g.*, the global structure of spacetime, dark energy and our cosmic future, parallel universes and fundamental versus environmental physical laws). (2) clearly requires (1) to determine whether to believe the conclusions. I argue that (1) also requires (2), since it affects the probability calculations for inflation's observational predictions.

A. The question refined, I

How did it all begin? Although this physics question has undoubtedly lingered for as long as humans have walked the Earth, the answer still eludes us. Yet since my grandparents were born, scientists have been able to refine this question to a degree I find truly remarkable.

First, the notion of "it all" was dramatically expanded by Edwin Hubble's 1925 discovery that the contemporary "universe" of nearby stars was merely part of one galaxy among countless others [1]. Today, most astronomers casually use the word "universe" to denote the spherical
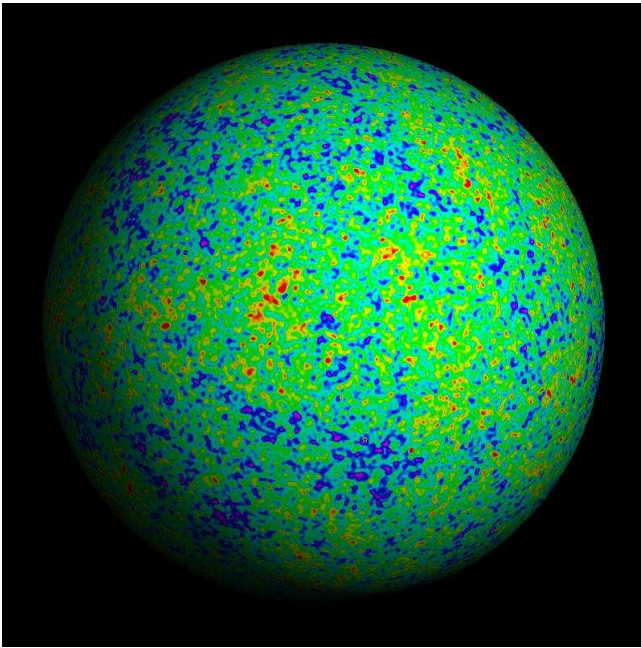

FIG. 1: Our entire observable universe is inside this sphere. Space continues outside the sphere, but an opaque glowing wall of hydrogen plasma hides it from our view. This is our best image so far of what this plasma sphere looks like, from [2], after cleaning out Galactic radio noise from the WMAP satellite observations. It has taken this light from the sphere's surface (known as the Cosmic Microwave Background radiation, CMB) over 13 billion years to reach us at the center.

volume shown in Figure 1, the cosmic event horizon containing about 10^{78} atoms and everything else we can in principle observe.

Second, it has become clear that this universe is not static, but dynamic and evolving. Spectacular recent measurements enabled by detector, computer and space technology have brought us a consistent quantitative picture of how our universe expanded and evolved from a hot, fiery event known as the Big Bang some 14 billion years ago. Our universe has expanded ever since the Big Bang, and this continuous stretching of space has both diluted and cooled the particles permeating it (Figure 2). As everything cooled, particles combined into progressively more complex structures. Quarks combined to form protons and neutrons. Later, when the cosmic temperature was comparable to the core of a star, fusion reactions combined neutrons and some of the protons into light elements like helium, deuterium and lithium. About 400,000 years after the Big Bang, the leftover protons combined with electrons to form electrically neutral hydrogen atoms, making the cosmos essentially transparent to light. Up until this point, matter was extremely uniform, with only tiny 10^{-5}-level density variations from place to place, but gravitational attraction gradually clumped atoms together into galaxies, stars and planets, allowing atoms to form complex structures like molecules, cells, people and societies.

By the time I was born, the question "How did it all begin?" had thus been refined to inquiring about what happened when our universe was less than a second old. This included some particularly disturbing sub-questions. For instance, why is space so big, so old and so flat, when generic initial conditions predict the curvature to grow over time and the density to fast approach either zero or infinity (the "flatness problem")? What mechanism generated the 10^{-5} level "seed" fluctuations (visible as cosmic microwave background fluctuations in Figure 1) out of which all cosmic structure grew, and what conspiracy caused these fluctuations to have nearly identical amplitude in regions of space that had never been in causal contact (the "horizon problem")?
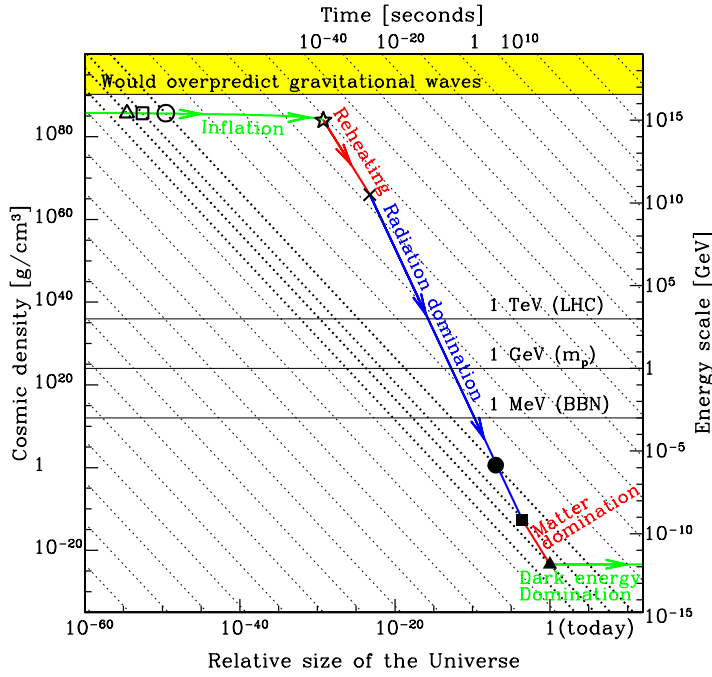
FIG. 2: The cosmic mean density (solid curve) is diluted as the Universe expands. Inflation is a period when there is almost no dilution, causing the expansion to accelerate, and corresponds to the curve decreasing slower than the dotted diagonal lines of slope -2. The two triangles lie on the same diagonal, which means that quantum fluctuations generated during inflation at the open triangle have been stretched into the horizon-scale fluctuations that we observe today at the filled triangle in the CMB (Figure 1). Detecting inflationary gravitational waves with CMB polarization would directly measure the shape of this cosmic density curve in the upper left corner of the plot, just as the dark energy experiments directly measure the same curve in the lower right corner.
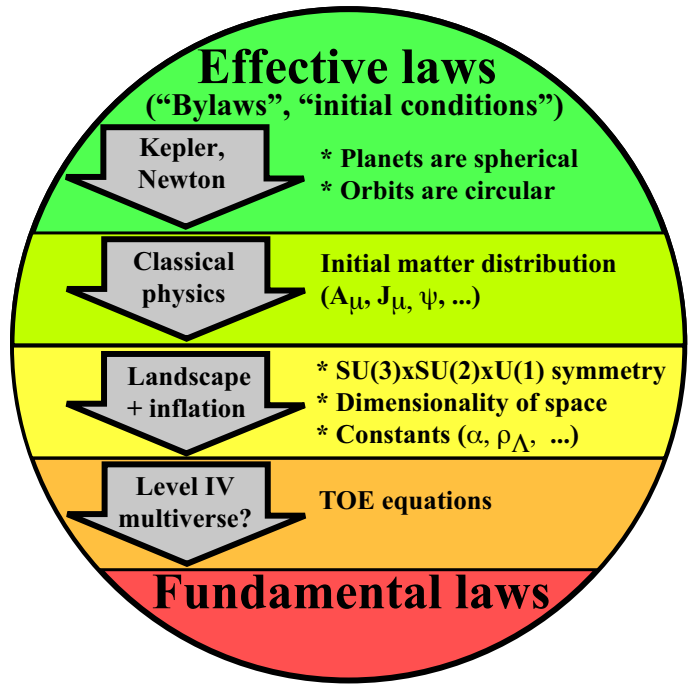

FIG. 3: The shifting boundary (horizontal lines) between fundamental laws and environmental laws/effective laws/initial conditions. Whereas Ptolemy and others had argued that the circularity of planetary orbits was a fundamental law of nature, Kepler and Newton reclassified this as an initial condition, showing that the fundamental laws also allowed highly non-circular orbits. Classical physics removed from the fundamental law category also the initial conditions for the electromagnetic field and all other forms of matter and energy (responsible for almost all the complexity we observe), leaving the fundamental laws quite simple. A TOE with a landscape and inflation reclassifies many of the remaining "laws" as initial conditions, since they can differ from one post-inflationary region to another, but since inflation generically makes each such region infinite, it can fool us into misinterpreting these environmental properties as fundamental laws. Finally, if the Level IV multiverse of all mathematical structures [22] exists, then even the "theory of everything" equations that physicists are seeking are merely local bylaws in Rees' terminology[23], differing across the ensemble.

B. The question refined, II

Around when I started high school in 1982, it was discovered that a process known as *inflation*, involving a nearly exponential stretching of space, could solve these and other problems in one fell swoop [3, 4, 5, 6, 7], and it soon emerged as the most popular theory for what happened very early on. Inflation is simple and elegant, requiring merely the existence of some form of matter that stubbornly refuses to have its density diluted as space expands (see [8, 9, 10, 11, 12, 13, 14, 15] for reviews). The cosmic density fluctuations are explained as the quantum fluctuations required by the Heisenberg uncertainty principle, magnified by the stretching of space and amplified by gravity.

Previous breakthroughs in theoretical physics like relativity theory and quantum mechanics not only solved old problems, but also transformed and deepened our understanding of the nature of physical reality. Inflation did the same. First of all, it soon became clear that inflation is generically eternal [8, 16, 17, 18, 19, 20, 21], so that

even though inflation has ended in the part of space that we inhabit (Figure 1), it still continues elsewhere and will ultimately produce an infinite number of other post-inflationary volumes as large as ours, forming a cosmic fractal of sorts.

Moreover, as illustrated in Figure 3, independent progress in theoretical physics has gradually shifted the borderline between "laws of physics" and "initial conditions" at the expense of the former. For example, a common feature of much string theory related model building is that there is a "landscape" of solutions, corresponding to spacetime configurations involving different dimensionality, different types of fundamental particles and different values for certain physical "constants". As an example, Table 1 lists the 30 parameters specifying the

Table 1: The 19 parameters of the $SU(3) \times SU(2) \times U(1)$ standard model of particle physics, compiled from [24], followed by 11 cosmological parameters as compiled in [25]. Massive neutrinos require additional parameters. Planck units are used, and μ^2 and λ are defined so that the Higgs potential is $V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$.

Parameter	Meaning	Measured value
g	Weak coupling constant	0.6425
θ_W	Weinberg angle	0.4908
g_s	Strong coupling constant	≈ 1.2
μ^2	Quadratic Higgs coefficient	$\sim -10^{-33}$
λ	Quartic Higgs coefficient	$\sim 1?$
G_e	Electron Yukawa coupling	2.94×10^{-6}
G_μ	Muon Yukawa coupling	0.000607
G_τ	Tauon Yukawa coupling	0.0102156233
m_u	Up quark Yukawa coupling	0.000016 ± 0.000007
m_d	Down quark Yukawa coupling	0.00003 ± 0.00002
m_c	Charm quark Yukawa coupling	0.0072 ± 0.0006
m_s	Strange quark Yukawa coupling	0.0006 ± 0.0002
m_t	Top quark Yukawa coupling	1.002 ± 0.029
m_b	Bottom quark Yukawa coupling	0.026 ± 0.003
$\sin\theta_{12}$	Quark CKM matrix angle	0.2243 ± 0.0016
$\sin\theta_{23}$	Quark CKM matrix angle	0.0413 ± 0.0015
$\sin\theta_{13}$	Quark CKM matrix angle	0.0037 ± 0.0005
δ_{13}	Quark CKM matrix phase	1.05 ± 0.24
$\theta_{\rm qcd}$	CP-violating QCD vacuum phase	$< 10^{-9}$
ξ_b	Baryon mass per photon $\rho_{\rm b}/n_\gamma$	$(0.49 \pm 0.03) \times 10^{-28}$
ξ_c	CDM mass per photon ρ_c/n_γ	$(2.7 \pm 0.2) \times 10^{-28}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11}\sum m_{\nu_i}$	$< 0.9 \times 10^{-28}$
$\Omega_{\rm tot}$	Spatial curvature	1.01 ± 0.02
ρ_Λ	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124}$
w	Dark energy equation of state	-1 ± 0.1
Q	Scalar fluctuation amplitude δ_H on horizon	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running of spectral index $dn_s/d\ln k$	$|\alpha| \lesssim 0.01$
r	Tensor-to-scalar ratio $(Q_t/Q)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained

standard models of particle physics and cosmology, some or all of which may vary across the landscape. Eternal inflation transforms such potentiality into reality, actually creating regions of space realizing each of these possibilities. However, each such region where inflation has ended is generically infinite in size, making it impossible for any inhabitants to travel to other regions where these apparent laws of physics are different.

If we define parallel universes as regions that are for all practical purposes disconnected (outside of causal contact for much longer than the lifetime of any observers), then these post-inflationary regions are an example thereof. They are labeled as "Level II" in Figure 4, which is my attempt from [22] to classify various types of parallel universes that have been discussed in the literature. Since each such Level 2 parallel universe is infinite in size, it consists of infinitely many spheres as in Figure 1 — this Level I multiverse is much less diverse, with the only difference between the spheres being the initial matter distribution (the initial conditions in the limited sense of classical physics — see Figure 3). Since the inflationary fluctuations are of quantum origin, inflation also populates the Level III multiverse (if quantum mechanics is applicable to this multiverse as a whole). We will

return to Level IV below.

So how did it all begin? Although inflation gives a beautifully unified answer to the conundra of the 1970's, we have seen that it still only refines the initial query further, leaving us with a number of questions:

1. How can we test whether inflation really happened?

2. What is the physics underlying inflation? (What is this hard-to-dilute substance?)

3. Why has inflation recently restarted? (What is the dark energy currently accelerating our universe?)

4. How did inflation begin? Or did it?

Thus addressing the question of how it all began is highly relevant also to other key questions in physics, such as the quest for the correct theory at the highest energies. Probing inflation might offer our best hope to test string theory and other quantum gravity candidates, since the early Universe is an unmanned physics experiment probing energy scales vastly exceeding those accessible in laboratories.

I. OBSERVATIONAL TESTS

This is an exciting time to tackle these question, because cosmological observations are finally becoming sensitive enough to help answer them. All inflation models solve the above-mentioned pre-1980 problems (the flatness problem, the horizon problem, etc.). In addition, as illustrated in Figure 5 and elaborated in [25], inflation may explain the values of as many as eight observable cosmological parameters (the last eight in Table 1), including those associated with dark energy. In the last few years, an avalanche of new cosmological data has revolutionized our ability to measure these parameters using tools such as the cosmic microwave background (CMB), galaxy clustering, gravitational lensing, the Lyman alpha forest, cluster abundances and type Ia supernovae [26, 27, 28, 29, 30], and I have worked hard to help carry this out in practice. In one suite of papers, I developed methods for analyzing cosmological data sets using information theory (e.g., [31, 32, 33, 34, 35, 36, 37] and applied them to various CMB experiments and galaxy redshift surveys (e.g., [38, 39, 40, 41]), often in collaboration with the experimentalists/observers who had gathered the data. Another series of papers tackled various "dirty laundry" issues such as microwave foregrounds and mass-to-light bias (e.g., [2, 42, 43, 44, 45, 46]). Other papers developed and applied techniques for clarifying the big picture in cosmology: comparing and combining diverse cosmological probes, cross-checking for consistency and constraining cosmological models and their free parameters (e.g., [27, 47, 48, 49, 50, 51]).

Level 1: Regions beyond our cosmic horizon
Features: Same laws of physics, different initial conditions
Assumptions: Infinite space, ergodic matter distribution
Evidence: - Microwave background meaurements point to
flat, infinite space, large-scale smoothness
- Simplest model

Level 4: Other mathematical structures
Features: Different fundamental equations of physics
Assumption: Mathematical existence = physical existence
Evidence: - Unreasonable effectiveness of math in physics
- Answers Wheeler/Hawking question:
"why these equations, not others"
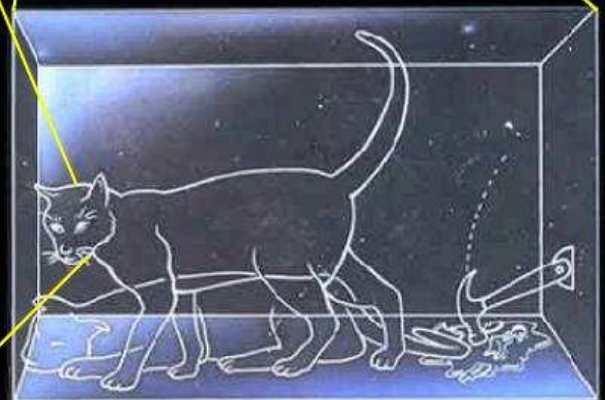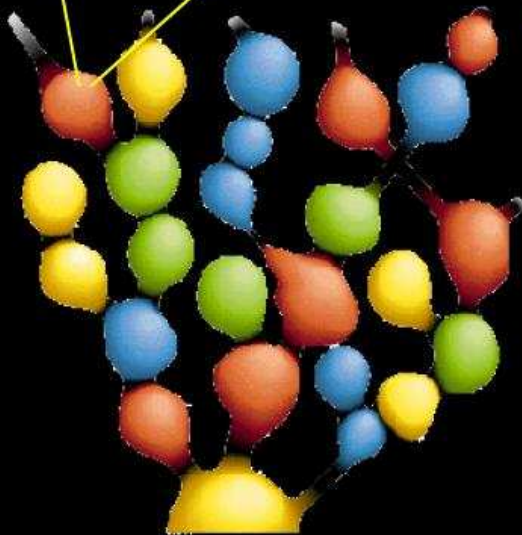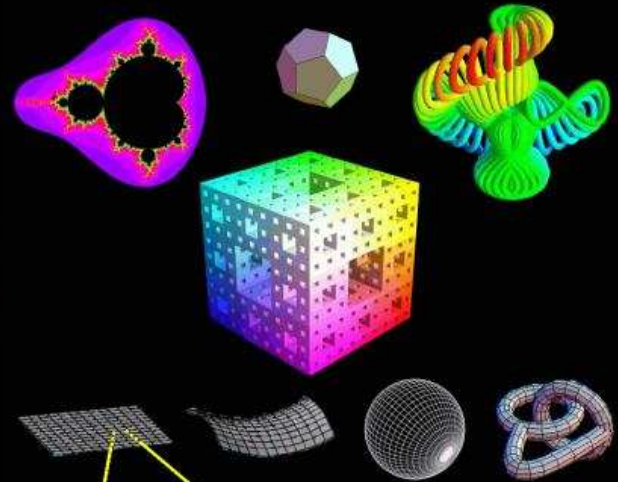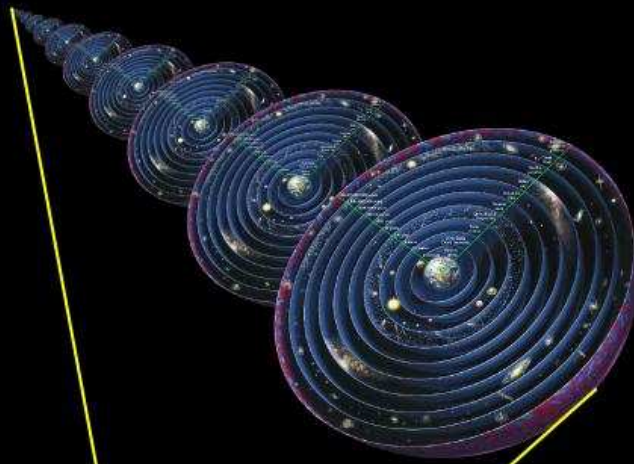
Level 2: Other post-inflation bubbles
Features: Same fundamental equations of physics, but perhaps
different constants, particles and dimensionality
Assumptions: Inflation occurred, multiple "vacua" exist
Evidence: - Inflation theory explains flat space, scale-invariant
fluctuations, solves horizon problem and monopole
problems and can naturally explain such bubbles
- Explains fine-tuned parameters

Level 3: The Many Worlds of Quantum Physics
Features: Same as level 2
Assumption: Physics unitary
Evidence: - Experimental support for unitary physics
- AdS/CFT correspondence suggests that
even quantum gravity is unitary
- Decoherence experimentally verified
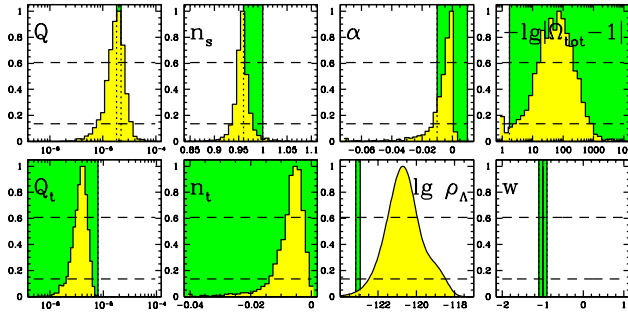- Mathematically simplest model

FIG. 5: Yellow/light grey cosmological parameter distributions show inflationary predictions for one of my examples from [25]. Green/dark grey regions show observational constraints (1σ) [27, 28]. ρ_Λ is in Planck units.

A robust prediction common to essentially all inflation models is that we should measure negligible curvature $\Omega_{\rm tot} = 1 \pm 10^{-5}$, strikingly confirmed by recent precision measurements such as $\Omega_{\rm tot} = 1.01 \pm 0.02$ [27] and $\Omega_{\rm tot} = 1.01 \pm 0.01$ [30]. Most models also predict approximately scale-invariant seed fluctuations ($n_s \approx 1$), in good agreement with the recent measurement $n_s = 0.98 \pm 0.03$ [27] (Figure 6). However, data are now getting sensitive enough to look for small departures from "vanilla" (scale-invariant, scalar, adiabatic and Gaussian) fluctuations, at least one of which is expected for essentially all published inflation models, so it is important and timely to work out the detailed predictions of competing models.

However, this theoretical calculation is proving surprisingly difficult! The reason is that most models predict a complicated spacetime with infinitely many observers [8, 16, 17, 18, 19, 20, 21], some of which measure different parameter values from others. The first 25 parameters in Table 1 will at least be constant within each Level II universe, but the last 5 can vary even between Level I universes, depending not only on which potential energy minimum the so-called inflaton field(s) rolled down into, but also on the path by which it got there. As discussed in [25], this means that generic inflation models (all models except ones that are perfectly symmetric around a single unique minimum) will predict not definite parameter values, but merely a probability distribution as in Figure 5. Moreover, as elaborated in [25], computing this probability distribution for what an observer should expect to measure (and hence making inflation testable) requires solving technical problems directly involving the more philosophical-sounding aspects of inflation:

1. The answer depends on the definition of "observer" (whether we compute the parameter distribution seen from a random point, a random proton, a random galaxy, a random planet, *etc.*).

2. The answer depends on the order(!) in which the infinitely many observers are counted.

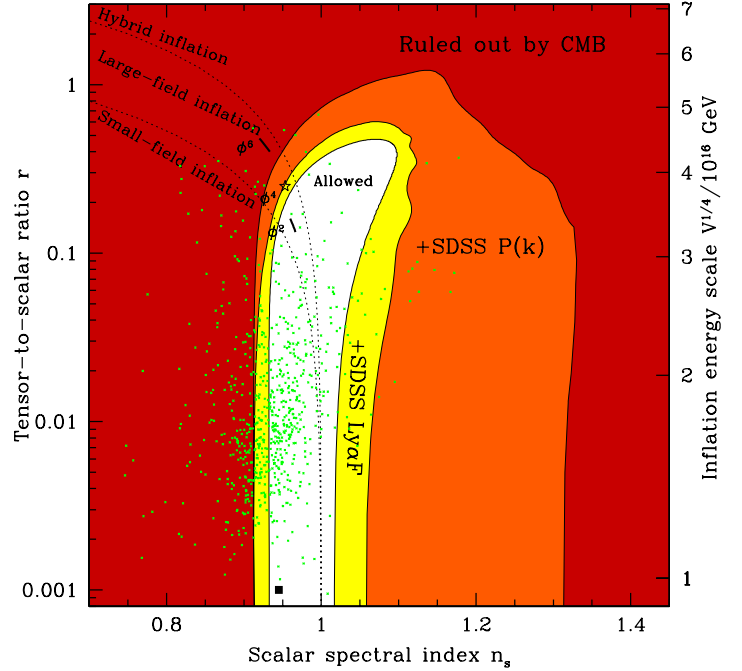3. The answer may depend on pre-inflationary initial conditions.

FIG. 6: Constraints and predictions in the (n_s, r)-plane show that observations are now finally starting to bump up against inflation theory in an interesting way. The nested shaded regions are ruled out at 95% confidence from WMAP CMB observations alone [26], when adding SDSS galaxy clustering information [27, 41] and when also adding SDSS Lyman α Forest information [28]. The green/grey points are the predictions from one of my simulations as described in [25], many producing a gravitational wave amplitude r large enough to be detectable by combining SDSS with the Planck CMB satellite in 2010 and measuring both n_s and r to an accuracy around 0.01 [52].

In spite of early difficulties, the daunting problem of how to predict probabilities was successfully overcome in both classical statistical mechanics and quantum mechanics, making me hopeful that inflation will follow suit. Building on [25], I am currently tacking these problems on several fronts, together with colleagues, as well as pursuing more hands-on calculations.

II. OUTLOOK

In the endevour to understand where everything comes from, two partial answers have in my opinion been found:

- Q: Where does the observed *matter* come from?
  A: Inflation can produce it all from almost nothing.

- Q: Where does the observed *complexity* come from?
  A: Parallel universes can produce it all from almost nothing, with the fundamental laws being simple and almost all the complexity existing only in the mind of the beholder, since the individual parallel universes require vastly more information to describe than the multiverse as a whole [53].

In conclusion, the age-old question "How did it all begin" has been dramatically refined in recent years, transformed into a quest to understand cosmological inflation and physics at the highest energies. In this quest, parallel experimental and theoretical progress has fruitfully connected mainstream empirical work to fundamental theoretical research that in turn has profound philosophical implications regarding our cosmic origin, our cosmic future, fundamental/environmental laws and parallel universes. In other words, looking ahead, if has never been more interesting than now to ask how it all began.

[1] E. P. Hubble, *The Observatory*, **48**, 139 (1925)
[2] M. Tegmark, A. de Oliveira-Costa, and A. Hamilton, *PRD*, **68**, 123523 (2003)
[3] A. Guth, *PRD*, **23**, 347 (1981)
[4] A. A. Starobinsky, *Phys. Lett. B*, **91**, 99;1980 (1980)
[5] A. D. Linde, *Phys. Lett. B*, **108**, 389 (1982)
[6] A. Albrecht and P. J. Steinhardt, *Phys. Rev. Lett.*, **48**, 1220 (1982)
[7] A. D. Linde, *Phys. Lett. B*, **129**, 177 (1983)
[8] A. D. Linde, *Particle Physics and Inflationary Cosmology* (Harwood: Switzerland, 1990)
[9] S. Dodelson, W. H. Kinney, and E. W. Kolb, *PRD*, **56**, 3207 (1997)
[10] D. H. Lyth and A. A. Riotto, *Phys. Rep.*, **314**, 1 (1999)
[11] A. R. Liddle and D. H. Lyth, *Cosmological Inflation and Large-Scale Structure* (Cambridge Univ. Press: Cambridge, 2000)
[12] H. V. Peiris *et al.*, *ApJS*, **148**, 213 (2003)
[13] W. H. Kinney, E. W. Kolb, A. Melchiorri, and A. Riotto, hep-ph/0305130, 2003
[14] A. R. Liddle and A. J. Smith, *PRD*, **68**, 061301 (2003)
[15] D. Wands, *New Astron. Reviews*, **47**, 781 (2003)
[16] A. Vilenkin, *PRD*, **27**, 2848 (1983)
[17] A. A. Starobinsky, *Fundamental Interactions* (MGPI Press, Moscow: p.55, 1984)
[18] A. A. Starobinsky 1986, in *Current Topics in Field Theory, Quantum Gravity and Strings, Lecture Notes in Physics, vol. 246*, ed. H. J. de Vega H J and N. Sanchez (Springer: Heidelberg.)
[19] A. S. Goncharov, A. D. Linde, and V. F. Mukhanov, *Int. J. Mod. Phys. A*, **2**, 561 (1987)
[20] D. S. Salopek and J. R. Bond, *PRD*, **43**, 1005 (1991)
[21] A. D. Linde, D. A. Linde, and A. Mezhlumian, *Phys. Rev. D*, **49**, 1783 (1994)
[22] M. Tegmark, *Ann. Phys.*, **270**, 1 (1998)
[23] M. J. Rees, *Our Cosmic Habitat* (Princeton Univ. Press: Princeton, 2002)
[24] S. Eidelman *et al.*, *Phys. Lett. B*, **592**, 1 (2004)
[25] M. Tegmark, *JCAP*, **2005-4**, 1 (2005)
[26] D. N. Spergel *et al.*, *ApJS*, **148**, 175 (2003)
[27] M. Tegmark *et al.*, *PRD*, **69**, 103501 (2004)
[28] U. Seljak *et al.*, astro-ph/0407372, 2004
[29] S. Cole, astro-ph/0501174, 2005
[30] D. J. Eisenstein, astro-ph/0501171, 2005
[31] M. Tegmark, A. N. Taylor, and A. F. Heavens, *ApJ*, **480**, 22 (1997)
[32] M. Tegmark, *Phys. Rev. Lett.*, **79**, 3806 (1997)
[33] M. Tegmark, A. J. S Hamilton, M. A. Strauss, M. S. Vogeley, and A. S. Szalay, *ApJ*, **499**, 555 (1998)
[34] M. Tegmark, *ApJL*, **480**, L87 (1997)
[35] M. Tegmark, *Phys. Rev. D*, **55**, 5895 (1997)
[36] M. Tegmark and A. de Oliveira-Costa, *Phys. Rev. D*, **64**, 063001 (2001)
[37] M. Tegmark, *Phys. Rev. D*, **56**, 4514 (1997)
[38] M. Tegmark, *ApJL*, **464**, L35 (1996)
[39] M. Tegmark *et al.*, *ApJL*, **474**, L77 (1996)
[40] M. Tegmark, A. J. S Hamilton, and Y. Xu, *MNRAS*, **335**, 887 (2002)
[41] M. Tegmark, M. Blanton, M. A. Strauss, F. S. Hoyle, D. Schlegel, R. Scoccimarro, M. S. Vogeley, D. H. Weinberg, I. Zehavi *et al.*, *ApJ*, **606**, 702 (2004)
[42] M. Tegmark, and G. Efstathiou, *MNRAS*, **281**, 1297 (1996)
[43] M. Tegmark, *ApJ*, **502**, 1 (1998)
[44] M. Tegmark, D. J. Eisenstein, W. Hu, and A. de Oliveira-Costa, *ApJ*, **530**, 133 (2000)
[45] M. Tegmark and P. J. E Peebles, *ApJL*, **500**, 79 (1998)
[46] M. Tegmark and B. C. Bromley, *ApJL*, **518**, L69 (1999)
[47] M. Tegmark, *ApJL*, **514**, L69 (1999)
[48] M. Tegmark and M. Zaldarriaga, *ApJ*, **544**, 30 (2000)
[49] M. Tegmark and M. Zaldarriaga, *Phys. Rev. Lett.*, **85**, 2240 (2000)
[50] M. Tegmark, M. Zaldarriaga, and A. J. S Hamilton, *Phys. Rev. D*, **63**, 043007 (2001)
[51] X. Wang, M. Tegmark, and M. Zaldarriaga, *Phys. Rev. D*, **65**, 123001 (2002)
[52] D. J. Eisenstein, W. Hu, and M. Tegmark, *ApJ*, **518**, 2 (1999)
[53] M. Tegmark, *Found. Phys. Lett.*, **9**, 25] (1996)